I. INTRO TO C

Hello World

```c
#include <stdio.h>

int main(void) {
 printf("Hello World!\n");
 return 0;
}
```

- `#include`: preprocessor inserts `stdio.h` contents
- `stdio.h`: contains `printf` declaration
- `main`: program starts here
- `void`: keyword for argument absence
- `{ }`: basic block/scope delimiters
- `printf`: prints to the terminal
- `\n`: newline character
- `return`: leave function, return value

Compiling

```
$ gcc hello.c -o hello
$ ./hello
Hello World!
```

Basic Data Types

- `char c = 5; char c = 'a';`
  one byte, usually for characters (1970: ASCII is fine)
- `int i = 5; int i = 0xf; int i = 'a';`
  usually 4 bytes, holds integers
- `float f = 5; float f = 5.5;`
  4 bytes floating point number
- `double d = 5.19562`
  8 bytes double precision floating point number

Basic Data Types – logic

- `int i = 5 / 2; //i = 2`
  integer logic, no rounding
- `float f = 5.0f / 2; //f = 2.5f`
  decimal logic for float and double
- `char a = 'a'/ 2 //a = 97 / 2 = 48`
  `char` interpreted as character by console

Basic Data Types – signed/unsigned

- `signed int i = -5 //i = -5` (two's complement)
- `unsigned int i = -5 //i = 4294967291`

Basic Data Types – short/long

- `short int i = 1024 //-32768...32767`
- `long int i = 1024 //-2147483648...2147483647`

Basic Data Types – more size stuff

- `sizeof int; sizeof long int; //4; 4;` (x86 32-Bit)
- use data types from `inttypes.h` to be sure about sizes:

```c
#include <inttypes.h>
int8_t i; uint32_t j;
```

Basic Data Types – const/volatile

- `const int c = 5;`
  `i` is constant, changing it will raise compiler error
- `volatile int i = 5;`
  `i` is volatile, may be modified elsewhere (by different program in shared memory, important for CPU caches, register, assumptions thereof)

Variables – local vs. global

```c
int m; // global variable

int myroutine(int j) {
 int i = 5 // local variable
 i = i+j;
 return i;
}
```

- *global variables* (`int m`):
  - lifetime: while program runs
  - placed on pre-defined place in memory
- basic block/function-local variables (`int i`):
  - lifetime: during invocation of routine
  - placed on stack or in registers

Variables – local vs. static

```c
int myroutine(int j) {
 static int i = 5;
 i = i+j;
 return i;
}

k = myroutine(1); // k = 6
k = myroutine(1); // k = 7
```

- static function-local variables:
  - saved like global variables
  - variable persistent across invocations
  - lifetime: like global variables

Printing

```c
int i = 5; float f = 2.5;
printf("The numbers are i=%d, f=%f", i, f);
```

- comprised of format string and arguments
- may contain format identifiers (`%d`)
- see also `man printf`
- special characters: encoded via leading backslash:
  - `\n` newline
  - `\t` tab
  - `\'` single quote
  - `\"` double quote
  - `\0` `null`, end of string

Compound data types

- `struct`ure: collection of named variables (different types)
- `union`: *single* variable that can have multiple types
- members accessed via . operator

```c
struct coordinate {
 int x;
 int y;
}

union longorfloat {
 long l;
 float f;
}

struct coordinate c;
c.x = 5;
c.y = 6;

union longorfloat lf;
lf.l = 5;
lf.f = 6.192;
```

Functions

encapsulate functionality (*reuse*)
code structuring (*reduce complexity*)
must be **declared** and **defined**
Declaration: states signature
Definition: states implementation (implicitly declares function)

```
int sum(int a, int b); // declaration

int sum(int a, int b) { // definition
  return a+b;
}
```

Header files

header file for frequently used declarations
use `extern` to declare global variables defined elsewhere
use `static` to limit scope to current file (e.g. `static float pi` in `sum.c`: no `pi` in `main.c`)

```
// mymath.h
int sum(int a, int b);
extern float pi;

// sum.c
#include "mymath.h"

float pi = 3.1415927;
int sum(int a, int b) {
  return a+b;
}

// main.c
#include <stdio.h>
#include "mymath.h"

void main() {
  printf("%d\n", sum(1,2));
  printf("%f\n", pi);
}
```

Data Segments and Variables

Stack: local variables
Heap: variables crated at runtime via `malloc()`/`free()`
Data Segment: static/global variables
Code: functions

Function overloading

no function overloading in C!
use arrays ore pointers

Pointers

```
int a = 5;
int *p = &a // points to int, initalized to point to a
int *q = 32 // points to int at address 32
int b = a+1;
int c = *p; // dereference(p) = dereference(&a) = 5
int d = (*p)+2 // = 7
int *r = p+1; // pointing to next element p is pointing to
int e = *(p+2) // dereference (p+2) = d = 7
```

Pointers – linked list

linked-list implementation via next-pointer

```
struct ll {
  int item;
  struct ll *next;
}

struct l first;
first.item = 123;

struct ll second;
second.item = 456;
first.next = &second;
```

Arrays

= fixed number of variables *continuously laid out in memory*

```
int A[5]; // declare array (reserve memory space)
A[4] = 25; A[0] = 24; // assign 25 to last, 24 to first elem
char c[] = {'a',5,6,7,'B'} // init array, length implicit
c[64] = 'Z' // NO bounds checking at compile/run (may raise
     protection fault)

// declare pointer to array; address elements via pointer:
char *p = c;
*(p+1) = 'Z'; p[3] = 'B'; char b = *p; // = 'a'
```

Strings

= array of `char`s terminated by `NULL`:

```
char A[] = { 'T', 'e', 's', 't', '\0' };
char A[] = "Test";
```

declaration via pointer:
`const char *p = "Test";`

common string functions (`string.h`):
length: `size_t strnlen(const char *s, size_t maxlen)`
compare:
`int strncmp(const char *s1, const char *s2, size_t n);`
copy: `int strncpy(char *dest, const char *src size_t n);`
tokenize: `char *strtok(char *str, const char *delim);`
(e.g. split line into words)

Arithmetic/bitwise operators

arithmetic operators:
`a+b`, `a++`, `++a`, `a+=b`, `a-b`, `a--`, `--a`, `a-=b`, `a*b`, `a*=b`, `a/b`, `a/=b`, `a%b`, `a%=b`
logical operators:
`a&b`, `a|b`, `a>>b`, `a<<b`, `a^b`, `~a`
difference pre-/post-increment:

```
int a = 5;
if(a++ == 5) printf("Yes"); // Yes
a = 5;
if(++a == 5) printf("Yes"); // nothing
```

operators in order of precedence:

```
(), [], ->, .
!, ++, --, +y, -y, *z, &=, (type), sizeof
*, /, %
+, -
<<, >>
<, <=, >, >=
==, !=
&
^
|
&&
||
?, :
=, +=, -=, *=, /=, %=, &=, ~=,=, «=, »=|
,
```

Structures

brackets only needed for multiple statements
`if/else`, `for`, `while`, `do-while`, `switch`
may use `break`/`continue`
switch: need break statement, otherwise will fall through

```
if(a==b) printf("Equal") else printf("Different");
for(i=10; i>=10; i--) printf("%d", i+1);
int i=10; while(i--) printf("foo");
int i=0; do printf("bar"); while(i++ != 0);

char a = read();
switch(a) {
  case '1':
    handle_1();
    break;
  default:
    handle_other();
    break;
}
```

Type casting

- <u>explicit casting</u>: precision loss possible
  `int i = 5; float f = (float)i;`
- <u>implicit casting</u>: if no precision is lost
  `char c = 5; int i = c;`
- <u>pointer casting</u>: changes address calculation
  `int i = 5; char *p = (char *)&i; *(p+1)= 5;`
- <u>type hierarchy</u>: „wider“/„shorter“ types
  `unsigned int` wider than `signed int`
  operators cast parameters to widest type
  Attention: assignment cast after operator cast

C Preprocessor

- modifies *source code* before compilation
- based on preprocessor *directives* (usually starting with `#`)
- `#include <stdio.h>`, `#include "mystdio.h"`:
  copies contents of file to current file
- only works with strings in source file
- completely ignores C semantics

Preprocessor – search paths

- `#include <file>`: system include, searches in:
  `/usr/local/include`
  `libdir/gcc/[target]/[version]/include`
  `/usr/[target]/include`
  `/usr/include`
  (target: arch-specific (e.g. i686-linux-gnu),
  version: gcc version (e.g. 4.2.4))
- `#include "file"`: local include, searches in:
  directory containing current file
  then paths specified by `-i <dir>`
  then in system include paths

Preprocessor – definitions

- defines introduce replacement strings (can have arguments, based on string replacement)
- can help code structuring, often leading to source code cluttering

```
#define PI 3.14159265
#define TRUE (1)
#define max(a,b) ((a > b) ? (a) (b))
#define panic(str) do { printf(str); for (;;) } while(0);

#ifdef __unix__
# include <unistd.h>
#elif defined _WIN32
# include <windows.h>
#endif
```

Preprocessor – predefined macros

- <u>system-specific</u>:
  `__unix__`, `_WIN32`, `__STDC_VERSION__`
- <u>useful</u>:
  `__LINE__`, `__FILE__`, `__DATE__`

Libraries

- = collection of functions contained in object files, glued together in dynamic/static library
- ex.: Math header contains declarations, but not all definitions
  ⇝ need to link math library: `gcc math.c -o math -lm`

```
#include <math.h>
#include <stdio.h>

int main() {
  float f = 0.555f;
  printf("%f", sqrt(f*4));
  return 0;
}
```

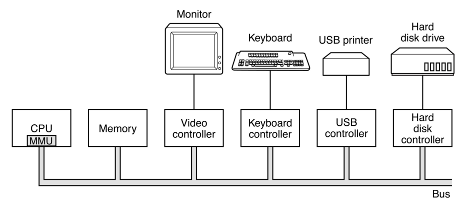
II. INTRODUCTION TO OPERATING SYSTEMS

What's an OS?

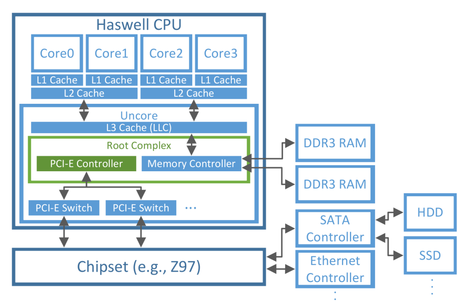
- <u>abstraction</u>: provides abstraction for applications
  manages and hides hardware details
  uses low-level interfaces (not available to applications)
  multiplexes hardware to multiple programs (*virtualisation*)
  makes hardware use efficient for applications
- <u>protection</u>:
  from processes using up all resources (*accounting*, *allocation*)
  from processes writing into other processes memory
- <u>resource managing</u>:
  manages + multiplexes hardware resources
  decides between conflicting requests for resource use
  strives for efficient + fair resource use
- <u>control</u>:
  controls program execution
  prevents errors and improper computer use
- ⇝ **no universially accepted definition**

Hardware Overview

- CPU(s)/devices/memory (conceptually) connected to common bus
- CPU(s)/devices competing for memory cycles/bus
- all entities run concurrently

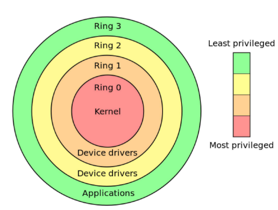


- today: multiple busses



Central Processing Unit (CPU) – Operation

- fetches instructions from memory, executes them (instruction format/-set depends on CPU)
- CPU internal registers store (meta-)data during execution (general purpose registers, floating point registers, instruction pointer (IP), stack pointer (SP), program status word (PSW),...)
- <u>execution modes</u>:
  user mode (x86: *Ring 3/CPL 3*):
    only non-privileged instructions may be executed
    cannot manage hardware → **protection**
  kernel mode (x86: *Ring 0/CPL 0*):
    all instructions allowed
    can manage hw with **privileged instructions**



Random Access Memory (RAM)

keeps currently executed instructions + data

today: CPUs have built-in *memory controller*

root complex connected directly via
„wire" to caches
pins to RAM
pins to PCI-E switches

Caching

RAM delivers instructions/data slower than CPU can execute

memory references typicalle follow *locality principle*:
spatial locality: future refs often near previous accesses (e.g. next byte in array)
temporal locality: future refs often at previously accessed ref (e.g. loop counter)

caching helps mitigating this memory wall:
copy used information temporarily from slower to faster storage
check faster storage first before going down **memory hierarchy**
if not, data is copied to cache and used from there

<u>Access latency</u>:
register: ∼1 CPU cycle
L1 cache (per core): ∼4 CPU cycles
L2 cache (per core pair): ∼12 CPU cycles
L3 cache/LLC (per uncore): ∼28 CPU cycles (∼25 GiB/s)
DDR3-12800U RAM: ∼28 CPU cycles + ∼ 50ns (∼12 GiB/s)

Caching – Cache Organisation

caches managed in hardware

divided into *cache lines* (usually 64 bytes each, unit at which data is exchanged between hierarchy levels)

often separation of data/instructions in faster caches (e.g. L1, see *harward architecture*)

cache hit: accessed data already in cache (e.g. L2 cache hit)

cache miss: accessed data has to be fetched from lower level

cache miss types:
compulsory miss: first ref miss, data never been accessed
capacity miss: cache not large enough for process working set
conflict miss: cache has still space, but collisions due to placement strategy

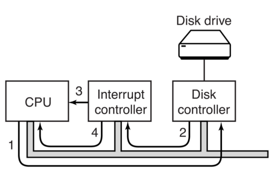
Interplay of CPU and Devices

I/O devices and CPU execute concurrently

Each device controller
- is in charge of particular device
- has local buffer

<u>Workflow</u>:

1. CPU issues commands, moves data to devices
2. Device controller informs APIC that operation is finished
3. APIC signals CPU
4. CPU receives device/interrupt number from APIC, executes handler



Device control

Devices controlled through their **device controller**, accepts commands from OS via **device driver**

devices controlled through device registers and device memory:
control device by writing device registers
read status of device by reading device registers
pass data to device by reading/writing device memory

2 ways to access device registers/memory:

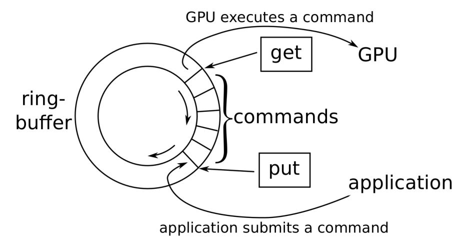
1. **port-mapped IO** (PMIO):
   use special CPU instructions to access port-mapped registers/memory
   e.g. x86 has different `in`/`out`-commands that transfer 1,2 or 4 bytes between CPU and device
2. **memory-mapped IO** (MMIO):
   use same address space for RAM and device memory
   some addresses map to RAM, others to different devices
   access device's memory region to access device registers/-memory

some devices use hybrid approaches using both

Device control – Nvidia general purpose GPU

memory-mapped ring-buffer and `put`/`get`-device

mapping can be exposed to application ⇝ application can submit commands in user-mode



Summary

The OS is an abstraction layer between applications and hardware (multiplexes hardware, hides hardware details, provides protextion between processes/users)

The CPU provides a separation of User and Kernel mode (which are required for an OS to provide protection between applications)

CPU can execute commands faster than memore can deliver instructions/data – memory hierarchy mitigates this memory wall, needs to be carefully managed by OS to minimize slowdowns

device drivers control hardware devices through PMIO/MMIO

Devices can signal the CPU (and through the CPU notify the OS) through interrupts

III. OS CONCEPTS

OS Invokation

OS Kernel does **not** always run in background!

Occasions invoking kernel, switching to kernel mode:

1. **System calls**: User-Mode processes require higher privileges
2. **Interrupts**: CPU-external device sends signal
3. **Exceptions**: CPU signals unexpected condition

System calls – motivation

Problem: protect processes from one another

Idea: Restrict processes by running them in user-mode

⇝ Problem: now processes cannot manage hardware,...
who can switch between processes?
who decides if process may open certain file?

⇝ Idea: OS provides **services** to apps
app calls system if service is needed (**syscall**)
OS checks if app is allowed to perform action
if app may perform action and hasn't exceeded quota, OS performs action in behalf of app in kernel mode

System Calls – Examples

`fd = open(file, how,...)` – open file for read/write/both

documented e.g. in `man 2 write`

overview in `man 2 syscalls`

System Calls vs. APIs

syscalls: interface between apps and OS services, limited number of well-defined entry points to kernel

APIs: often used by programmers to make syscalls
e.g. `printf` library call uses `write` syscall

common APIs: Win32, POSIX, C API

System Calls – implementation

trap instruction: single syscall interface (entry point) to kernel
switches CPU to kernel mode, enters kernel in same, predefined way for all syscalls
system call dispatches then acts as syscall multiplexer

syscalls identified by number passed to trap instruction
syscall table maps syscall numers to kernel functions
dispatcher decides where to jump based on number and table
programs (e.g. `stdlib`) have syscall number compiled in!
⇝ never reuse old numbers in future kernel versions

Interrupts

devices use interrupts to signal predefined conditions to OS
reminder: device has „interrupt line“ to CPU
e.g. device controller informs CPU that operation is finished

programmable interrupt controller manages interrupts
interrupts can be **masked**
masked interrupts: queued, delivered when interrupt unmasked
queue has finite length ⇝ interrupts can get lost

noteable interrupt examples:

1. *timer-interrupt*: periodically interrupts processes, switches to kernel ⇝ can then switch to different processes for fairness
2. *network interface card* interrupts CPU when packet was received ⇝ can deliver packet to process and free NIC buffer

when interrupted, CPU

1. looks up **interrupt vector** (= table pinned in memory, contains addresses of all service routines)
2. transfers control to respective **interrupt service routine** in OS that handles interrupt

interrupt service routine must first save interrupted processe's state (instruction pointer, stack pointer, status word)

Exceptions

sometimes unusual condition makes it impossible for CPU to continue processing

⇝ **Exception** generated within CPU:

1. CPU interrupts program, gives kernel control
2. kernel determines reason for exception
3. if kernel can resolve problem ⇝ does so, continues **faulting instruction**
4. kills process if not

Difference to Interrupts: interrupts can happen in any context, exceptions always occur asynchronous and in process context

OS Concepts – Physical Memory

up to early 60s:
- programs loaded and run directly in *physical memory*
- program too large → partitioned manually into *overlays*
- OS then swaps overlays between disk and memory
- different jobs could obeserve/modify eachother

OS Concepts – Address Spaces

bad programs/people need to be isolated

Idea: give every job the illusion of having all memory to itself
every job has own *address space*, can't name addresses of others
jobs always and only use virtual addresses

Virtual Memory – indirect addressing

Today: every CPU has built-in **memory management unit** (*MMU*)

MMU translates virtual addresses to physical addresses at every store/load operation

⇝ address translation protects one program from another

Definitions:
Virtual address: address in process' address space
Physical address: address of real memory

Virtual Memory – memory protection

MMU allows kernel-only virtual addresses
- kernel typically part of all address spaces
- ensures that apps can't touch kernel memory

MMU can enforce *read-only* virtual addresses
- allows safe sharing of memory between apps

MMU can enforce execute disable
- makes code injection attacks harder

Virtual Memory – page faults

not all addresses need to be mapped at all times
- MMU issues *page fault* exception when accessed virtual address isn't mapped
- OS handles page faults by loading faulting addresses and then continuing the program
- ⇝ memory can be **over-committed**: more memory than physically available can be allocated to application

page faults also issued by MMU on illegal memory accesses

OS Concepts – Processes

= program in execution („instance“ of program)

each process is associated with a **process control block** (*PCB*)
contains information about allocated resources

each process is associated with a virtual **address space** (*AS*)
- all (virtual) memory locations a program can name
- starts at 0 and runs up to a maximum
- address 123 in AS1 generally $\neq$ address 123 in AS2
- indirect addressing ⇝ different ASes to different programs
- ⇝ protection between processes

OS Concepts – address space layout

address spaces typically laid-out in different **sections**
- memory addresses between sections **illegal**
- illegal addresses ⇝ page fault
- more specifically calles **segmentation fault**
- OS usually kills process causing segmentation fault

Stack: function history, local variables

Data: Constants, static/global variables, strings

Text: Program code